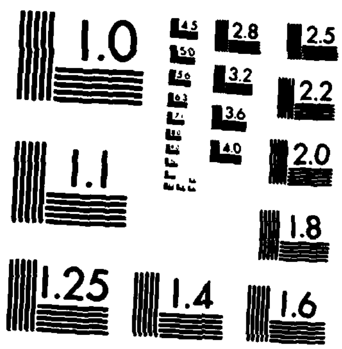
AD-A172 219 DEVELOPMENT OF A CCD BASED SOLAR SPECKLE IMAGING SYSTEM 1/1
(U) SMITHSONIAN ASTROPHYSICAL OBSERVATORY CAMBRIDGE MA
P NISENSON ET AL 03 FEB 86 AFGL-TR-86-0044-1
UNCLASSIFIED F19628-83-K-0025 F/G 3/2 NL



AFGL-TR-86-0044 (I)

AD-A172 219

Development of a CCD Based Solar Speckle Imaging System

PETER NISENSON
ROBERT V. STACHNIK
ROBERT W. NOYES

Smithsonian Institution
Astrophysical Observatory
60 Garden Street
Cambridge, MA 02138

3 February 1986

Final Report
1 March 1983 - 30 September 1985

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

This technical report has been reviewed and is approved for publication.

(Signature) Richard R. Radick Contract Manager	(Signature) S. L. Keil Branch Chief

FOR THE COMMANDER

(Signature)
R. C. Sagalyn
Division Director

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFGL-TR-86-0044 (I)
6a. NAME OF PERFORMING ORGANIZATION: Smithsonian Institution Astrophysical Observatory; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Air Force Geophysics Laboratory
6c. ADDRESS (City, State and ZIP Code): 60 Garden Street, Cambridge, MA 02138	7b. ADDRESS (City, State and ZIP Code): Hanscom AFB, MA 01731
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F19628-83-K-0025
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61101F	1L1R	3G	AA

11. TITLE (Include Security Classification) Development of a CCD Based Solar Speckle Imaging System

12. PERSONAL AUTHOR(S) Nisenson, Peter; Stachnik, Robert V.; Noyes, Robert W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 3/1/83 TO 9/30/85	1986 February 3	28

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	High Resolution Solar Imaging
			CCD Camera
			Speckle Imaging Charge Cou...

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes the program at the Harvard-Smithsonian Center for Astrophysics (CfA) to develop software and hardware for the purpose of obtaining high angular resolution images of the solar surface. The program included the purchase of a CCD imaging system; an extensive laboratory and remote site testing of the camera system; the development of a software package for speckle image reconstruction which was eventually installed and tested at the Sacramento Peak Observatory; and experiments of the CCD system (coupled to an image intensifier) for low light level, narrow spectral band solar imaging.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Richard Radick		AFGL/PHS

TABLE OF CONTENTS

I.	INTRODUCTION	1
II.	THE CCD SYSTEM	2
III.	OBSERVING RUNS: APRIL, 1983 TO SEPTEMBER, 1985	4
IV.	SEPTEMBER 1985 DATA RECORDING RUN	6
V.	DATA PROCESSING AND EVALUATION FOR SEPTEMBER, 1985 SPO OBSERVING RUN	8
VI.	LOW LIGHT-LEVEL IMAGING	10
VII.	SPECKLE IMAGING SOFTWARE	12
FIGURES		19

I. INTRODUCTION

The principal goals of this program were the development of hardware and software for high angular resolution imaging of the solar surface. To this end, a CCD camera was purchased by the Center for Astrophysics, extensively tested in the laboratory, and used for acquisition of solar data on a number of observing runs at the Sacramento Peak Observatory Tower telescope and at the Kitt Peak Mcmath telescope. In a parallel effort, software for reduction of the solar data using speckle image reconstruction algorithms was developed at CfA and, at the conclusion of the program, installed and tested at SPO. Since SPO now has CCD cameras equivalent to the CfA camera, this program has performed nearly all of the operations required to implement a permanent, on-line facility for high resolution imaging at SPO. Since images of the highest quality may only be obtained when weather conditions are good (and features such as sunspots are visible on the disk), having a full capability at the observatory is critically important in achieving optimal results from these techniques. This is emphasized by the very limited success in obtaining high quality data on the observing runs during this program: good data were only recorded in the final run at SPO, at a time when the Sun was almost devoid of the high contrast features needed for guiding.

Successful reconstructions of solar features have still only been obtained with high light level, wideband data. Substantial effort was applied, during this program, to developing a low light level capability for imaging in spectral lines with narrow band filters. Lens coupling of the CCD to an image intensifier allowed reasonable data recording through a 1/8 Angstrom filter. However, residual effects of the photon noise bias prevented successful reconstruction from this data. Use of either a photon camera (which has been very successful on faint nightime data), or a more sensitive CCD which does not need intensification, appears to be the only solution to this problem.

Overall, we believe that this has been a very successful program, which has led to numerous important developments in high angular resolution solar imaging, and to the establishment of a facility at SPO which can be used for "routine" recording and processing of new data.

II. THE CCD SYSTEM

A CCD camera and controller was purchased from Photometrics, Inc. of Tucson, Arizona for solar image data recording. The CCD was an RCA SID53612 unthinned chip which has good red sensitivity but poor direct blue sensitivity. Since it was not thinned, it does not suffer from the severe interference effects which are well known in thinned devices and which would have been

a particular problem with the narrow spectral band recording necessary for speckle imaging. Photometrics provided a mounted chip in a thermo-electrically cooled housing (to -30 degrees C) and a computerized camera controller which allows simple operation of the system from high level software commands. The chip operates with two 256x320 fields either in a "TV" mode in which the image is recorded on one half of the chip, then shifted to the other half (which is covered) for readout, or in a shuttered direct expose and readout mode. Photometrics provided a 12 bit high speed (8 microseconds/pixel) A/D from which the data must be read into a computer or stored. Initially, we used our own VCR digital recording system which encodes data on a video carrier. Toward the end of this project, we implemented (with the help of SPO personnel) direct digital storage on magnetic tape through the Tower telescope Perkin-Elmer 3220 computer. This system allowed frame rates of 3.5 frames/sec with the VCR recorder or 2 frames per second through the Perkin-Elmer.

A major but subtle problem was found when the CCD was used in the mode in which it was lens-coupled to an image intensifier for low light level operation in narrow-band spectral line data recording. Individual detected photons were seen to have vertical "tails" associated with them, the tail length being proportional to the vertical position in the field. After extensive testing and the return of the CCD system to Photometrics, it was determined that the streaking was due to poor charge-transfer efficiency and that one of the vertical clock lines on the chip

was defective. While this was not a repairable defect (and, as a further complication, this type of CCD chip was discontinued by RCA so no substitute could be obtained), it was found that by masking the defective half of the chip, the other half could be used in the shuttered (not the TV) mode with only a small loss in duty cycle. Unfortunately, this defect was sufficiently subtle that it was only discovered well into the program. However, the problem was sufficiently serious to make worthless all data recorded on the chip operating in the TV mode. Fortunately, the best data sets were recorded after repair, in the 1985 SPO run.

III. OBSERVING RUNS: APRIL, 1983, TO SEPTEMBER, 1985

During the 30 month interval from April, 1983, to September, 1985, we had six solar observing runs. Only the first and last of these aimed at acquisition of broad spectral band data. The other runs used the CCD camera coupled to an image intensifier package to obtain narrow band data. The runs are briefly summarized below:

14 - 19 April, 1983: McMath telescope observing run using Kitt Peak CID 11B primarily in direct (non-intensified) imaging mode. Some experiments were conducted to test feasibility of using the chip lens-coupled to an intensifier. This run led to acquision of data resulting in a paper demonstrating recon- struction of a small solar pore and of a portion of a spot

penumbra. Power spectrum analysis of the penumbra showed the presence of structure at a resolution approaching the diffraction limit of the telescope.

9 - 11 August, 1983: SPO Vacuum Tower run using the newly-acquired Photometrics Inc. CCD. Monsoon conditions severely hampered the observations but we were able to test the new apparatus, test the Graves image stabilizer at SPO and plan for direct digital recording and display of our data using the Tower computer. During this run data were digitally recorded on our VHS-format cassette recorder.

1 - 4 October, 1983: SPO Vacuum Tower run again using the Photometrics camera, this time in intensified mode. Observations were made through the UBF with the Graves stabilizer located in front of the UBF optics. Again, we suffered from poor weather but were able to demonstrate tranfer of imagery, via a CAMAC interface, to the Tower computer. Overlapping scheduling permitted useful interaction with the Lockheed group headed by Dr. Robert Smithson.

7 - 11 July, 1984: McMath telescscope run using the H-alpha filter and intensified CCD. We had previously learned of the problem of poor CCD charge transfer efficiency in one direction leading to image degradation which, while visually subtle, was almost certainly fatal to the image recovery process. Seeing was poor during much of the run. Data recovery was hampered by the

photon noise compensation problem.

7 - 13 September, 1984: Joint run with SPO's Dr. Richard Radick at the McMath telescope. These observations were performed with the SPO 0.12 Angstrom calcium K-line filter which yielded excellent images, however, no sunspots were observable, making use of the image stabilizer impossible, and the corresponding low level of solar activity meant that relatively little structure of exceptional interest was present in any case. Data from this run was used extensively for testing image reconstruction from the image intensifier coupled CCD, however no high quality images were recovered, due to the photon noise bias problems associated with the camera.

6 - 12 September, 1985: This very successful run is described in the next section.

IV. SEPTEMBER 1985 DATA RECORDING RUN

A 6 - 12 September, 1985, data collecting run on the Sacramento Peak Vacuum Tower telescope resulted in acquisition of only one good data set, however the data collected were of extraordinary quality. During the run seeing was fairly good but, except for the morning of September 9th, the Sun was completely featureless. Even on the 9th, the only obvious feature on the

entire disk was a small, evolving pore, too small for the agile mirror image stabilizer to lock onto, but sufficient for computer recentering. Our observations of this object yielded data of exceptional quality.

Data were collected with the CfA (Photometrics, Inc.) CCD camera/controller interfaced to the Tower telescope Perkin-Elmer 3220 computer. The computer was capable either of writing images to magnetic tape or of displaying them in raw or bias and flat field corrected format. Twelve tapes containing 105 data sets, each consisting of 100 frames, were recorded between 8:21 and 11:52, for an average time between data sets of 2 minutes. Frames were obtained at a rate of 2 per second. Exposure times were 5 milliseconds through a 50 Angstrom filter centered on H-alpha (656 nm). Also in the optical path was a neutral density 1.1 filter. The Sun's elevation varied from 22 to 61 degrees during the observations. Dark bias and flat field frames were taken approximately hourly and calibration grids were also recorded. The CCD was operated in a 2x2 pixel binned mode, yielding a 128x128 element field. The Solar image was magnified to give an angular field of 7 arcseconds, affording Nyquist over-sampling of 0.056 arcsecond per pixel. The telescope diffraction limit at this wavelength is 0.17 arcseconds.

During the data taking sequence, substantial evolution of the pore was evident, and the feature eventually faded into the surrounding granulation. Recording was terminated when it was no

longer possible to guide on the object.

V. DATA PROCESSING AND EVALUATION FOR SEPTEMBER, 1985, SPO OBSERVING RUN

Upon return to the laboratory, our first priority was preliminary processing of the data (flat field and bias compensation) and direct image inspection.

Initially, the pore was a single structure. A second feature then appeared to the east and, some time later, a third pore appeared one or two arcseconds to the south. The pore to the east subsequently disappeared and the northern and southern feature merged. The southern feature then dissipated, as did the northern feature , leaving only background granulation. Throughout this documentation of the evolution and disappearence of a pore, the data quality is spectacular. Substantial high frequency detail is seen in all the input frames as are occasional hints of what may be rudimentary penumbral structure. Initial examination of power spectra from several data sets indicate that the high frequencies extend to the telescope diffraction limit. All twelve tapes have now been bias and flat field corrected and we are beginning a process of power spectrum analysis for survey and diagnostic purposes and of image reconstruction for selected data sequences.

Examples of the raw data are contained in figures 1, 2 ,3 and 4. Each figure consists of 16 successive images from a data set. The first, taken at time t=0, (0825), shows the two east-west pores, though not clearly differentiated, with a hint of some structure below them. Figure 2 shows the structure of the pore at t=1:25, when the southern feature has undergone considerable development and the northern pair has shrunk to a single pore. In both sets of images substantial complex structure is visible in the surrounding granulation field. Figure 3 (t=2:45) shows only a slight darkening at the center of the granulation field, making guiding increasingly difficult. Figure 4 is identical to figure 3 but is reproduced at enhanced contrast to show the complex stucture remaining at the site of the nearly-disappeared pore. In all of the image sets, the top 9 lines of the 128x128 images were of low quality and were replaced by reflecting lines 10 through 18 into them.

Substantial effort has been directed to solving the problems associated with border interaction effects. One approach was to reduce the amount of image motion with respect to the borders by finding the pore centroid, then extracting a 64x64 array around that point from the larger 128x128 array. The 64x64 arrays were processed and reconstructed in the usual fashion. This approach results in a rather small processed area and suffers from the fact that the seeing disk size is a substantial fraction of the field diameter. As a consequence, phase fluctuations between adjacent

fourier sample points may exceed pi, with resultant failure of the phase recovery procedure and truncation of speckle patterns near edges of the field, resulting in reconstruction degradation similar to that encountered with loss of isoplanatism. Early tests with the centered 64x64 arrays have not been been promising but experiments are continuing.

A second approach has been to perform the centroiding (done by first contrast inverting, followed by location of the centroid of the now bright pore within a subarea known to contain the feature) and then to multiply by a moving gaussian window centered at the location of the image centroid. The effect of this procedure is to produce intermediate images in which image structure near the border is supressed, thus reducing the effect of the borders. Experiments with this procedure have been promising and are continuing.

VI. LOW LIGHT LEVEL IMAGING

The CCD system utilizes a thick RCA chip (512x320) which has insufficient sensitivity for direct narrow wavelength band data recording, particularly in the blue spectral region. Since many of the most interesting solar imaging problems require observations in the Ca II K-line spectral region, this is a severe

limitation. It was hoped that reimaging the output face of a blue sensitive image intensifier onto the CCD would solve this problem. While data recording appeared to be successful and integrated images looked potentially interesting, the speckle image reconstruction processes did not produce images of a quality comparable to the broadband reconstructions generated from direct CCD imaging in previous observations. The problems in the reconstruction process appear to be similar to ones encountered when data were recorded with the ISIT video system: correction of the photon noise bias cannot be performed with sufficient accuracy. In low light level data sets, the signal of interest sits on a bias whose amplitude is proportional to the number of detected photons, and whose shape is determined by the point response of the detector. The fainter the detected source, the larger the ratio of bias to signal and the greater the accuracy of correction required. With a photon counting camera such as the CfA PAPA detector, this noise bias may be corrected exactly since the number of detected photons is known, and each photon is detected as a delta function. With the intensified CCD system, the number of photons must be estimated from the power spectrum of the data itself, and the detected photon shape is determined from the combined point spread functions of the intensifier, optical relay system and the CCD. In the high light level regime in which the CCD is used directly, the photon noise bias level is very small, so no correction is required. However, the intensified data increases the bias level by several hundred times. Estimates of the bias

shape were produced using low light level flat fields recorded at the time of the data recording. However, inaccuracies in these estimates appear to be too great, and substantial degrading effects of the noise bias remain in the reconstructions, despite our best efforts to eliminate them.

The most promising solution to the low light level problem is to use a more sensitive detector for the narrow band experiments. New CCD chips generated by Tektronics have two orders of magnitude more sensitivity than the RCA chip, and also have greatly improved blue response without suffering the interference fringing effects which have been a problem with other thinned chips. These CCDs should be usable without intensification, and substitution of a new chip in the Photometrics camera system should be straightforward. Until the time that we are able to make use of a new CCD chip, we plan to continue experiments in broadband imaging with the current, unintensified system. In the high light level regime, the photon noise bias error is neglegible, so the image reconstruction routines are quite successful.

VII. SPECKLE IMAGING SOFTWARE

Implementation of speckle imaging procedures, which include application of a version of the Knox-Thompson algorithm for phase recovery, to solar image processing was an important part of the

scientific program. The software was written on a Digital Equipment Corporation Vax 780 at the CfA in Fortran 77. A version of this code was sent to Sacremento Peak where it was converted to run on the Perkin-Elmer 3240 computer by on the scientific and technical staff at SPO, with our assistance. The completion of the conversion of this software package and its testing with CCD data recorded at the tower was carried out during our September, 1985 SPO data run. Details of this run and the results of the tests are included in section V.

Appendix A contains listings of the speckle processing code. We will outline the overall functionality of the programs and include suggestions for their use on solar data. We have not included the programs which read in the raw data and perform the conventional formatting and CCD dark field and flat fielding corrections, since these routines are very machine and detector specific. The software package consists of two major programs, SAC128.FOR and CCDFIX.FOR.

SAC128.FOR performs the data fourier transforms and yields the integrated power spectra, Knox-Thompson arrays and direct sums, writing the output arrays to disk. This program assumes that the data have been pre-screened for bad frames and that the detector pixel scale and format size has been properly chosen during the data recording to meet the requirements of the Knox-Thompson algorithm. Since the phase differences are calculated for adjacent pixels, the atmospheric correlation length must

exceed that scale, implying that during data taking, the seeing disk diameter was less than half the full recording field size. Each frame is fourier transformed using a routine which takes full advantage of the symmetry in the transform of a real array (the input image) into a half-plane complex array. Two separate arrays are then generated, one from each quadrant of the transform with the first row common to both arrays. This is a convenient approach for the later reconstruction operations, though during the phase reconstruction, a full four quadrant array is reconstructed to allow taking full advantage of the redundancies in the transform. The data integration arrays are then generated in the subroutine GENPD.FOR and saved on disk for the reconstruction process.

CCDFIX.FOR performs the image or autocorrelation reconstruction with a wide variety of smoothing, filtering and display options, including several options for reweighting the speckle power spectrum to compensate for the atmospheric transfer function and some options for correcting for the photon noise bias if intensified narrow band data (where photon noise becomes significant) is being processed. The integrated array is accepted into the program in either CfA array processor data format, or in a VAX format, depending on which was used for data integration. In general, short data sets or test runs are generated with the VAX while long integrations (usually only for low light level data) are run with the array processor. If the data are in array processor format, then the subroutine PHPACK.FOR unpacks it into a

form which matches the VAX format.

Reconstructions are carried out with several different approaches to the problem of reweighting the speckle transfer function. When a point reference source is available, as is the case for nighttime observations, reweighting is always carried out by deconvolution of the object spectrum by the reference star spectrum. In the solar imaging problem, reference point sources are not available (except from analytic estimators), so reweighting is carried out by either a low pass filtering operation, or by subtracting a weighted version of the long exposure transform from the object spectrum. Neither of these methods provides very accurate rewighting. However, since the solar data are almost always very slowly varying in intensity over the small reconstruction field (a few arcseconds), the subtraction technique is nearly equivalent to just changing the dc level, and interactive adjustment of a reweighting multiplier allows recovery of a good estimate of the image. After reweighting, the final transfer function of the process may be adjusted, with either a high frequency rolloff or enhancement, depending on the signal-to-noise in the recovered spectrum.

CCDFIX also writes out intermediate files which prove extremely useful both as diagnostics of the data and the of processes, and as additional information which can be used for interpreting the reconstructions. Displays of the power spectrum, reweighted amplitude and reconstructed phase (represented as

intensities, 0 to 1 for phase angles ranging from zero to 2*Pi) can be written to disk. After recovery of both the amplitude and phase in the image transform, a fourier transform inverts the data to an image plane, for display of the final reconstruction. Alternatively, the image autocrrelation, which is just the transform of the reweighted power spectrum, may be generated. The program also displays a plot of a cut through the image maximum row to a terminal screen.

The major reconstruction subroutines are REC4CFC.FOR which reconstructs the phases from the Knox-Thompson arrays; AMP5CA.FOR and AMP5CB.FOR which calculate the autocorrelation with deconvolution or long exposure subtraction reweighting, respectively; and REC5CA.FOR AND REC5CB.FOR which perform equivalent operatiions to the AMP5 programs and also combine the amplitudes with phases for image reconstruction.

Probably, the most critical subroutine is the one called PHAVS.FOR, which is called from REC4FC. This routine calculates the phases of the image transform from the Knox-Thompson arrays. In order to obtain an optimized estimate of the phase which utilizes all of the inherent redundancy and symmetries in the input arrays, the equivalent of a least-squares fit of the output phase array to the Knox-Thompson arrays is calculated iteratively. An error criterion is displayed for each iteration which allows an estimate of the convergence. It has been our experience that between 5 and 20 iterations are required for a suitably optimized

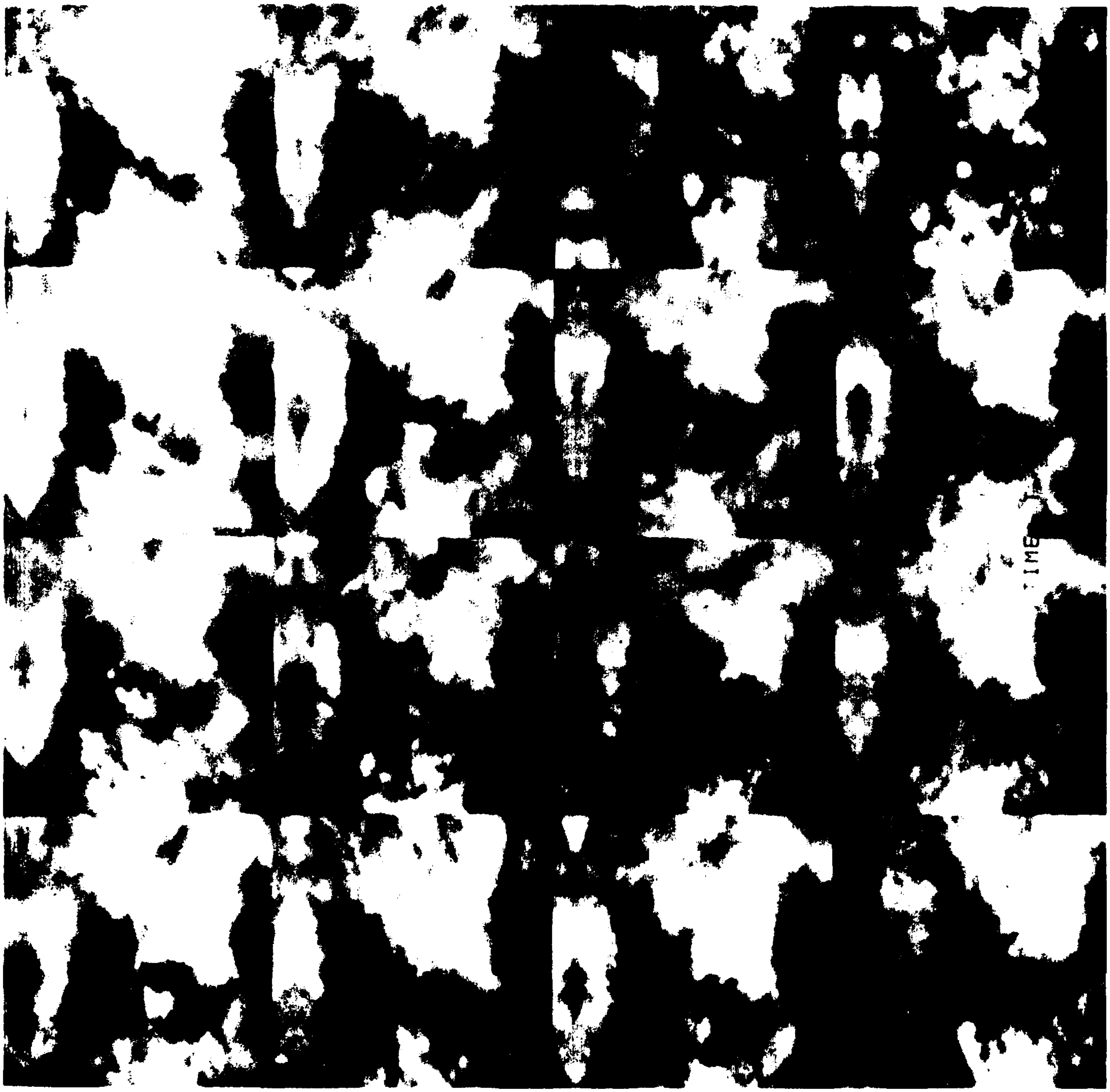
image.

There are a large number of features of these programs that have not been described here. However, it is our experience that there is no substitute for hands-on use of the programs with either real or simulated data. Varying the parameters while monitoring the resulting reconstructions should rapidly give the user a feel for which parameters are more important, and which may stay at nominal values. We cannot over-emphasize the necessity of having good diagnostic tools, particulary image display and plotting devices, in order to extract the best results from a given data set. We also point out that the exact operation of the programs and choices of parameters is highly dependant on the specifics of the data set being processed, with particular weight being placed on the signal-to-noise, seeing quality and detector artifacts.

Finally, we also include listings of new versions of the integration and reconstruction programs, plus relevant subroutines, which have just been developed for the specific purpose of processing data sets such as those obtained in the recent SPO (September, 1985) run. With a well defined small dark feature, such as the small pore recorded in that run, even though the image stabilizer could not lock onto the image, digital centering and gaussian masking appear to eliminate border effects, which had been a problem with unstabilized images. The relevant programs are:

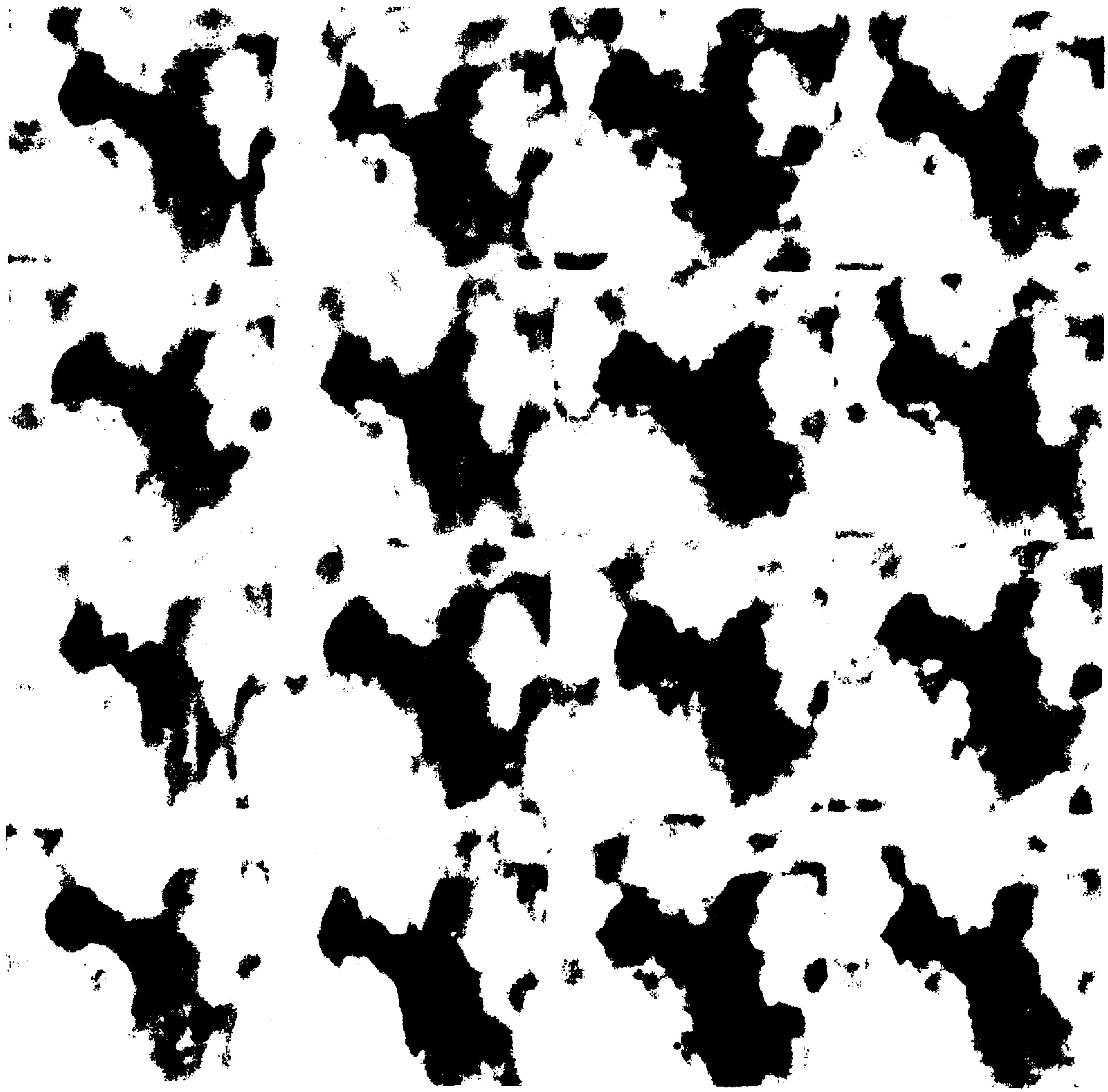
SAC128S.FOR replaces SAC128.FOR for data integration. It calls a subroutine CH64S.FOR which inverts the image, finds the center of the feature, excludes frames where decentering is too great, and either selects a centered 64x64 pixel array, or multiplies the full 128x128 by a gaussian centered on the feature. The rest of the program operates in the same manner as the old SAC128.FOR. GSAC.FOR replaces CCDFIX.FOR for reconstruction. The only major differences between the programs are that GSAC reinverts the image and reweights the reconstruction to compensate for the gaussian weighting.

F I G U R E S



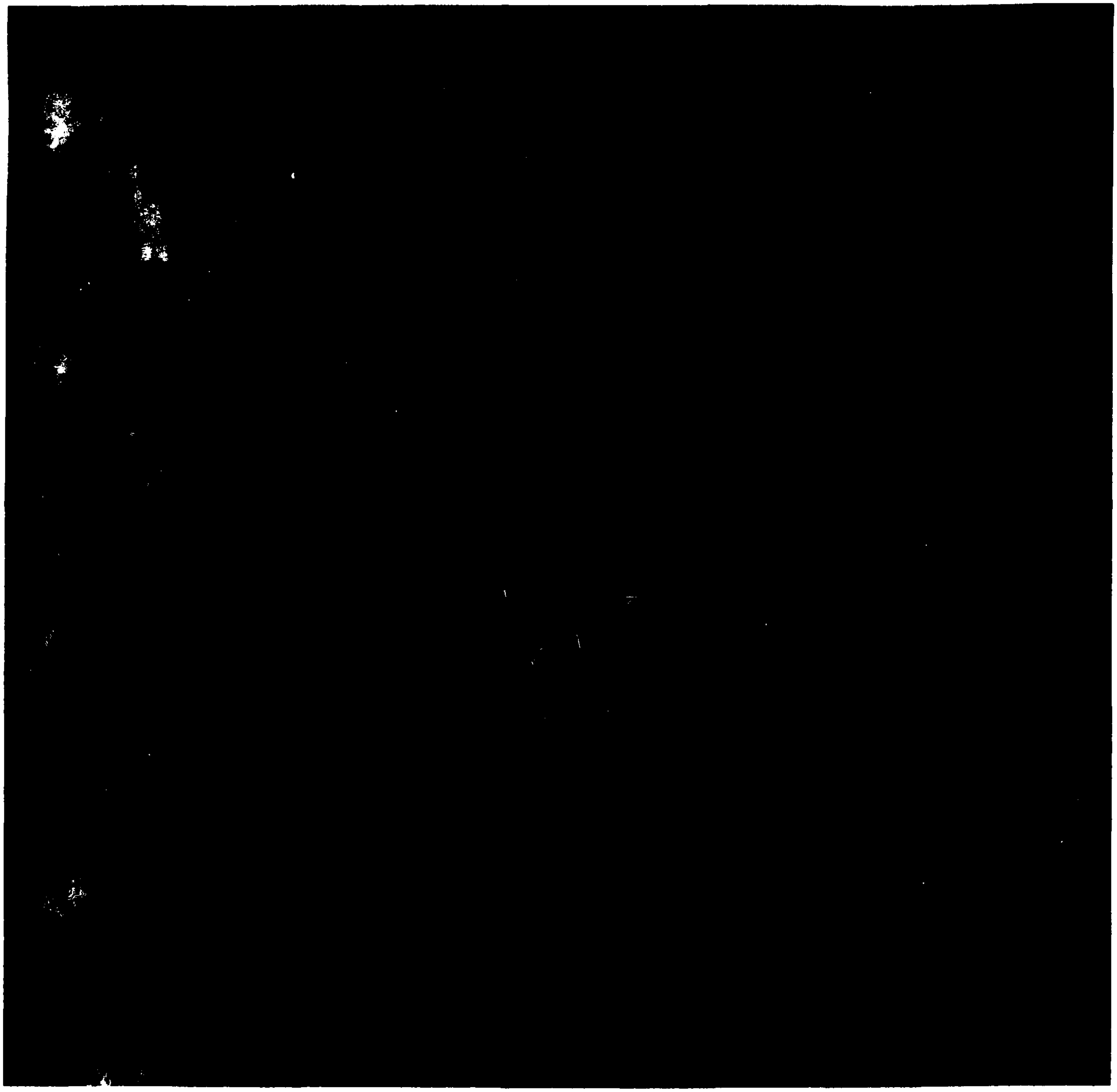
TIME = T

Figure 1



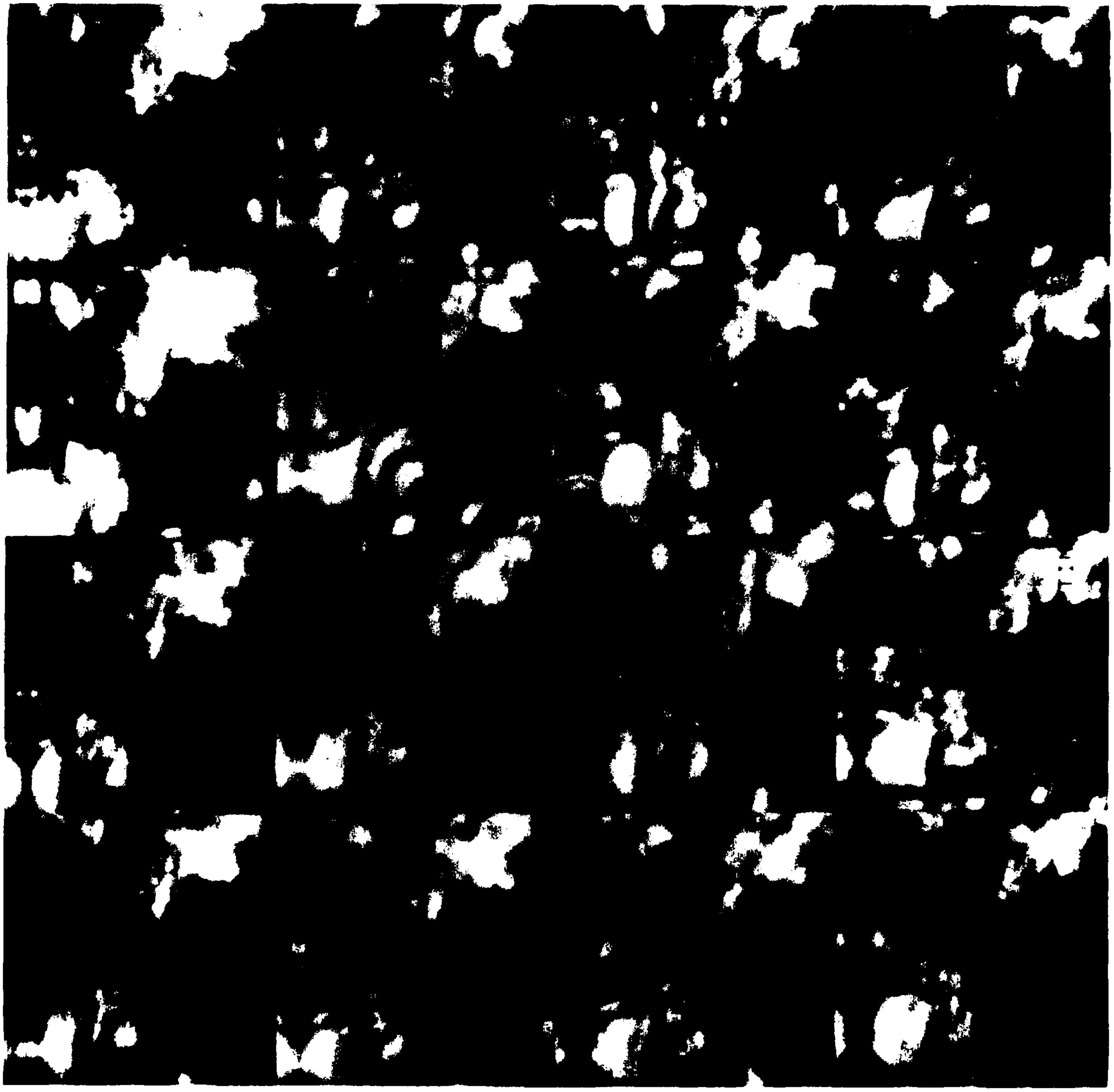
TIME = T + 1:25

Figure 2



TIME = T + 2:45

Figure 3



TIME = T+2:45

Figure 4

END

10-86

DTIC